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ERPs reveal the temporal dynamics of auditory word recognition in specific language impairment

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ABSTRACT

We used event-related potentials (ERPs) to compare auditory word recognition in children with specific language impairment (SLI group; $N = 14$) to a group of typically developing children (TD group; $N = 14$). Subjects were presented with pictures of items and heard auditory words that either matched or mismatched the pictures. Mismatches overlapped expected words in word-onset (cohort mismatches; see: DOLL, hear: *dog*), rhyme (CONE – *bone*), or were unrelated (SHELL – *mug*). In match trials, the SLI group showed a different pattern of N100 responses to auditory stimuli compared to the TD group, indicative of early auditory processing differences in SLI. However, the phonological mapping negativity (PMN) response to mismatching items was comparable across groups, suggesting that just like TD children, children with SLI are capable of establishing phonological expectations and detecting violations of these expectations in an online fashion. Perhaps most importantly, we observed a lack of attenuation of the N400 for rhyming words in the SLI group, which suggests that either these children were not as sensitive to rhyme similarity as their typically developing peers, or did not suppress lexical alternatives to the same extent. These findings help shed light on the underlying deficits responsible for SLI.

1. Introduction

Spoken word recognition involves processing incoming auditory information and mapping it onto the knowledge of sounds in a language in order to arrive at a meaning. This is a complex process that can break down at any level: poor spoken language comprehension can occur as a result of deficits in basic acoustic processing, impaired knowledge of speech sounds (phonological processing), abnormal word-level knowledge (lexical processing), and/or deficits in processing meaning (semantics). Difficulties with spoken word recognition are a hallmark of specific language impairment (SLI), a developmental impairment occurring in about 7% of children (Tomblin et al., 1997a,b) characterized by delayed language development despite otherwise typical development and exposure to adequate learning opportunities (see Bishop and Snowling, 2004;

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Schwartz, 2009, for reviews). Despite the widespread acknowledgment of spoken word recognition deficits in SLI, the level of breakdown in the word recognition process remains a matter of considerable debate. Deficits in children with language impairment have been observed at the levels of acoustic processing (Tallal and Piercy, 1973; Tonnquist-Uhlén et al., 1996; Bishop and McArthur, 2004; McArthur and Bishop, 2004; Shafer et al., 2011), speech perception (Joanisse et al., 2000; Ziegler et al., 2005; Robertson et al., 2009; Archibald and Joanisse, 2012), syntax (Norbury et al., 2001; van der Lely, 2005), lexical processing (Seiger-Gardner and Brooks, 2008; McMurray et al., 2010), semantics (McGregor et al., 2002; Seiger-Gardner and Schwartz, 2008), phonological short-term memory and working memory (Archibald and Gathercole, 2006; Leonard et al., 2007a,b; Alloway et al., 2009; Helenius et al., 2009), as well as other processes. There is also an ongoing debate regarding whether these deficits are the result of a specific deficit in grammar (van der Lely, 2005) or impaired phonology (Joanisse and Seidenberg, 1998; Joanisse, 2004), or are instead due to more general deficits in procedural learning (Ullman and Pierpont, 2005) or difficulties in tracking statistical regularities in speech input (Evans et al., 2009; Hsu and Bishop, 2010).

In recent years, there has been an increasing trend in using online language measures to study this population to better understand the nature of the underlying deficit (e.g., Shafer et al., 2005; McMurray et al., 2010). The advantage of online measures is the ability to assess the neurocognitive substrates of speech processing as it unfolds, whereas traditional measures such as phoneme categorization and discrimination provide a measure at the end point of processing. Thus, using time-sensitive measures to examine the different elements of spoken word processing as auditory words unfold might shed light on the nature of the underlying cause of SLI. In the present study we focus on characterizing these underlying component processes using event related potentials (ERPs) to test cortical responses to spoken words (for a review, see Newman et al., 2012).

ERPs are well suited to addressing the nature of the underlying deficit in SLI, given our ability to assess specific cognitive processes based on the specific components that appear to be related to them. For example, in spoken word recognition, dissociable ERP components have been identified that index the different stages of processing from acoustic information toward meaning: early sensory processing is thought to be marked by the N100 (Näätänen and Picton, 1987), prelexical processing by the phonological mapping negativity (PMN; Connolly and Phillips, 1994; Newman and Connolly, 2009), and later, word-level processing by the N400 (Kutas and Hillyard, 1984). Furthermore, we can employ a task that modulates these components in distinct ways such that we can infer the stages of processing underlying overall deficits in spoken word recognition. For this, we have turned to the picture–word matching task used by Desroches et al. (2009), in which subjects judge whether a spoken word matches or mismatches a visually presented picture. In this task, the picture is presented first, to set up an expectation of auditory input, which might then be violated in various ways, based on the phonological relationship between a presented versus expected word. Different types of phonological relationships, such as words that overlap in onsets versus rimes, lead to different types of mismatch effects. The nature of these effects gives some insight into how a particular group of subjects processes auditory words.

In the current study, we examined the time course of auditory word recognition in SLI. To do this, we used the same design as Desroches et al. (2009) such that mismatches shared either word-initial phonemes with expected words (cohort mismatches; see: DOLL, hear: *dog*), rime (rhyme mismatches; see: CONE, hear: *bone*), or no phonemes at all (unrelated mismatches; see: SHELL, hear: *mug*). We compared auditory word recognition between children with SLI and typically developing age-matched controls, and specifically looked at three ERP components: the N100, the PMN, and the N400. For the N100, we compared ERP responses for the baseline “match” condition, to investigate potential group differences in auditory sensory processing, as this has been shown in prior studies (Tonnquist-Uhlén et al., 1996; McArthur and Bishop, 2004). However, one should note that these prior studies have tended to look specifically at non-speech sounds (Tonnquist-Uhlén et al., 1996; McArthur and Bishop, 2004), or have used synthetic speech (Breier et al., 2003; McArthur and Bishop, 2005), and so the use of natural speech in this study offers an interesting contribution in this regard. Conversely, for the PMN and N400, we compared responses to certain types of mismatches (cohorts versus rhymes) in order to elucidate whether these two groups might show differences in phonemic and lexical processing. This was based on evidence from prior studies that these groups show differences in processing consonants (Sussman, 1993; Burlingame et al., 2005) and vowels (Shafer et al., 2005) as well as differential sensitivity to onset versus rhyme similarity (Gray et al., 2012; Seiger-Gardner and Brooks, 2008; Shafer et al., 2004). Taken together, analysis of these three components offered us an opportunity to tease apart the component processes underlying deficits in spoken word recognition in SLI.

2. Materials and methods

2.1. Subjects

Fourteen children with specific language impairment (SLI group) and fourteen typically developing children (TD group) were recruited from the London, Ontario area. Both children and their parents gave their informed consent/assent to participate. The SLI group ranged in age from 8;4 to 12;9 ($M = 9;9$) and the TD group ranged in age from 8;4 to 12;7 ($M = 10;4$). Importantly, age was not significantly different between groups [$t(26) = 1.169$, $p = .25$, Cohen’s $d = .44$]. Prior to taking part in the experimental task, children performed a series of standardized tests to assess their language abilities as well as their nonverbal IQ. Results of these standardized tests are summarized in Table 1. Critically, the TD and SLI groups differed in standardized scores on receptive grammar tests (either TROG-2; Bishop, 1989, or CELF-4; Semel et al., 2003), which

Table 1
Mean performance on standardized language and IQ measures in the typically developing (TD) and specific language impairment (SLI) groups.

Measure	Variable	TD group (N = 14)	SLI group (N = 14)
Age		10;4 (1;3)	9;9 (1;4)
Receptive grammar	TROG-2 or CELF-4	113.43 (11.17)[a]	82.21 (7.22)
Non-verbal IQ	WISC-IV Block Design and Matrix Reasoning or TONI-III	105.64 (10.26)[b]	96.57 (6.14)
Socioeconomic status	Neighborhood-level median family income	$93,501[c]	$64,229

Note. Values in parentheses represent standard deviations.

[a] Standard scores. All children performed the TROG-2, except for three in the TD group, and one in the SLI group who performed the CELF-4 instead.

[b] Standard scores. This is the mean of the WISC-IV Block Design and Matrix Reasoning scores for all children except for three in the TD group, and one in the SLI group, who performed the TONI-III instead.

[c] Determined based on the postal code of each child's family residence, and calculated by taking the median value across all children in each respective group. Retrieved from Statistics Canada (2006).

were significantly lower in the SLI group than they were in the TD group [$t(26) = 8.78$, $p < .001$, Cohen's $d = 3.32$]. In addition, all children exhibited normal non-verbal IQ, as indicated by scaled scores above 7 (i.e., within one standard deviation of the mean) on either the Block Design or Matrix Reasoning subtests of the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003) or a score above 85 on the Test of Nonverbal Intelligence – Third Edition (TONI-III; Brown et al., 1997).[1] However, even though all children scored in the normal range, non-verbal IQ was significantly higher in the TD group compared to the SLI group [$t(26) = 2.84$, $p < .01$, Cohen's $d = 1.07$]. In addition, we also obtained estimates of socioeconomic status using neighborhood-level median family income based on the postal code for each child's family residence (Statistics Canada, 2006). Median family income was marginally higher in the TD group than it was in the SLI group [$W = 137.5$; $p = .07$]. The findings for NVIQ and SES data raise the possibility that one or both factors might explain the group differences in speech processing measures. To address this, groupwise differences in subsequent ERP measures were correlated with both non-verbal IQ and SES to assess whether these variables could account for observed effects.

2.2. Stimuli and procedures

All auditory words were monosyllables spoken in isolation as produced by an adult female native speaker of English. Words were recorded at 48,828 Hz and resampled to 44,100 Hz, and were presented to the right ear via ER-3A insert earphones (Etymotic Research, Elk Grove Village, IL). For each target word, mismatches were selected that either shared word-initial CV with targets but differed in word-final phonemes (cohort mismatches; see: DOLL, hear: *dog*), shared word-final phonemes but differed in onset consonants (rhyme mismatches; see: CONE, hear: *bone*), or were completely phonologically unrelated to the target (unrelated mismatches; see: SHELL, hear: *mug*). The three mismatch conditions did not differ significantly from one another in logarithmic frequency (Zeno et al., 1995) [$F(2,60) = 1.20$, $p = .31$, $\eta_p^2 = .04$], number of neighbors (Davis, 2005) [$F(2,60) = .94$, $p = .35$, $\eta_p^2 = .03$], nor duration of the auditory stimuli [$F(2,60) = .82$, $p = .43$, $\eta_p^2 = .03$] or phonemic length [$F(2,60) = .33$, $p = .71$, $\eta_p^2 = .01$]. Color pictures matching these words were presented on a white background on a 19-in. CRT monitor. To ensure they were familiar with the names of the pictures, children completed a naming task prior to experimental trials in which they were asked to say aloud what they thought was the most appropriate name for each picture. In cases where they stated a word different from the intended name, they were given the intended name (e.g., saying *cup* instead of MUG). When the intended name was given, all children acknowledged that they were familiar with the intended name.

In experimental trials, subjects were first presented with a fixation cross for 250 ms, following which a picture of an item was presented for 1500 ms. Following this, and while the picture remained on screen, subjects heard an auditory word (mean duration of 576.5 ms, with a standard deviation of 84.3 ms), and were then asked to press a button on a keypad with their right hand indicating whether the auditory word matched the picture. Subjects were asked to respond as quickly and accurately as possible as soon as the auditory word was fully presented. After indicating their response, subjects saw a blank screen for 1000 ms before the onset of the next trial; as the mean RT across subjects and items was 1117 ms, the total trial length was therefore 3867 ms on average. Overall, there were 186 trials in the experiment, half of which were match trials (and the other half mismatch trials; 31 trials of each of the three mismatch types, for a total of 93 mismatch trials). These were counterbalanced such that each item appeared twice as a picture (once as a match and once as a mismatch) and twice as a sound (once as a match and once as a mismatch) over the course of the experiment, ensuring that every time a subject was presented with a picture of an item or heard a word, it was as likely to be a match as a mismatch trial. Furthermore, subjects were assigned to one of two pseudorandom stimulus sequences that balanced for whether each auditory item was a match or mismatch the first time it was encountered. Prior to the experiment, subjects completed six trials in order to acquaint them with the procedure. All materials and procedures were approved by the non-medical Research Ethics Board at the University of Western Ontario.

[1] The last four children recruited for this study were tested as part of a larger study on language, reading, and mathematics in the London, Ontario community. The subtests employed in this larger study were in some cases different from those used in earlier testing. As such, the latter four children recruited for the study were tested using CELF-4 and TONI-III rather than TROG-2 and WISC-IV respectively.

2.3. EEG data acquisition

EEG data were collected at a sampling rate of 500 Hz using Acquire 4.2 (Neurosoft Inc., El Paso, TX) and a 32-channel cap with sintered Ag/AgCl electrodes (Quik-Caps; Neurosoft Inc., El Paso, TX) positioned according to the international 10-20 system and referenced to the nose tip. Impedances were kept below 5 kΩ. Data were amplified at a gain of 500 using a SynAmps amplifier and filtered online using 60 Hz notch and 0.1–100 Hz bandpass filters. ERPs were segmented into epochs spanning 200 ms pre-stimulus to 1200 ms post-stimulus onset. Data were then filtered offline using a 24 dB zero phase shift digital bandpass filter (0.1–30 Hz), and baseline corrected to the mean voltage of the 200 ms pre-stimulus interval. Trials containing blinks and other artifacts were removed using a maximum voltage criterion of ±100 μV 0–700 ms post-stimulus onset at the fifteen electrodes subjected to data analysis. In addition, incorrect trials were rejected. After this, an average of 143/186 trials were retained across all trials in the TD group (distributed across the four word types as follows: cohort 23/31, rhyme 24/31, unrelated 23/31, match 73/93), and 116/186 were retained for the SLI group (cohort 19/31, rhyme 20/31, unrelated 19/31, match 58/93). The number of accepted trials was significantly different between groups [$t(26) = 2.32$, $p = .03$, Cohen's $d = .91$], raising the concern that any observed group differences are an artifact of this difference. To address this we quantified mean signal to noise ratio (SNR) for each individual across the fifteen electrodes used in subsequent data analyses, by taking the root mean square voltage for the 0–700 ms post-stimulus interval divided by the RMS voltage of the pre-stimulus baseline (−200 to 0 ms). Computed SNRs were not significantly different between groups [$t(26) = 0.247$, $p = .81$, Cohen's $d = .10$]. The highly similar SNR values across groups suggest that differences in the number of accepted trials cannot account for observed groupwise differences.

2.4. Analysis of ERP data

For both groups, we analyzed the following ERP components: the N100, the PMN, and the N400, as has been done in prior picture–word matching studies (e.g., Archibald and Joanisse, 2012).[2] Windows of analysis were determined by visual inspection, and were defined as follows: N100 (80–180 ms), PMN (250–330 ms), N400 (350–550 ms) and late N400 (550–650 ms). For the N100, we have restricted our analyses to match trials and compared these between groups, as the match condition represented the most reliable assessment of baseline auditory word processing given that the auditory input matched expectations. An inspection of the data showed that there was considerable variability in the latency of the N100 component, so we elected to use an adaptive analysis to account for possible latency differences between subjects and groups; namely, 50% fractional area latency. This was calculated by first taking the sum of the absolute values of voltage measurements within the N100 window, and then determining the latency at which half of this sum was reached. Analyses of the PMN, N400, and late N400, in contrast, looked at mean amplitude and focused specifically on mismatch effects across the word type conditions; as a result, we computed difference waves by subtracting the respective match conditions from each of the respective mismatch conditions. This had the benefit of eliminating any groupwise difference in absolute voltages in the baseline match condition; instead, analyses were performed on relative voltage differences between the word type conditions.

For each analysis window in each group, we selected fifteen electrodes which are considered to give sufficient coverage of the scalp in order to differentiate the components of interest (Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8; Newman et al., 2003). We then analyzed ERPs using a 'column' approach (Holcomb and Grainger, 2006) in which we performed separate repeated measures analyses of variance for lateral, medial, and midline electrodes. Midline electrodes were divided into three regions: anterior (Fz), central (Cz), and posterior (Pz), and for this column we performed mixed ANOVAs with within-subjects factors of region (3) and for PMN, N400, and late N400 analyses, word type (3; cohort, rhyme, unrelated), and a between-subjects factor of group (TD children and children with SLI). Medial electrodes were also divided into three regions (anterior: F3, F4; central: C3, C4; posterior P3, P4), and we added an additional within-subjects factor of hemisphere (left or right). Similarly, for lateral electrodes, we divided electrodes into three regions (anterior: F7, F8; central: T7, T8; posterior P7, P8), and also added a within-subjects factor of hemisphere. We then performed separate mixed ANOVAs for lateral and medial electrodes with within-subjects factors of hemisphere (2), region (3), and for the PMN, N400, and late N400, word type (3), as well as a between-subjects factor of group (2). All analyses of variance were conducted using conservative degrees of freedom (Greenhouse and Geisser, 1959). In cases where there was a significant interaction of a within-subjects factor with group, we performed follow-up tests by analyzing simple effects. In cases where there was a significant interaction of a within-subjects factor with word type, we performed step-down analyses using simpler repeated measures ANOVAs. Last, in cases where there was a main effect of word type, we performed Bonferroni corrected pairwise comparisons between word type conditions.

3. Results

3.1. Behavioral data

Behavioral data for one child in the TD group was not recorded due to equipment failure. For the remaining children, we calculated mean reaction time and mean accuracy for the matching judgment, which are presented in Table 2.

[2] There are also apparent differences between word type conditions in later portions of the waveform, marked by a late positivity that begins around 750 ms. Importantly though, we did not have a priori hypotheses regarding this component, nor did this later-going effect appear to distinguish among conditions in a way that was not apparent in the earlier-going components. Thus, in the interest of brevity we have constrained our analyses to only these three components.

Table 2
Mean reaction time and mean percent accuracy for the matching judgment relative to word onset.

Condition	TD group (N = 13)		SLI group (N = 14)	
	RT (ms)	Accuracy	RT (ms)	Accuracy
Cohort	1173 (40)	93.2 (1.4)	1304 (56)	84.8 (3.3)
Rhyme	1073 (38)	96.9 (1.0)	1122 (64)	93.4 (2.0)
Unrelated	1044 (44)	95.6 (1.8)	1108 (58)	92.8 (3.1)
Match	1055 (41)	96.2 (0.7)	1102 (54)	90.4 (2.8)

Note. Values in parentheses represent standard errors.

Trials were removed from behavioral analyses if reaction times were more than 2.5 standard deviations above or below condition-wise means. In addition, only correct trials were included in the RT analysis. For RTs, a mixed design ANOVA with word type as a within-subjects factor and group as a between-subjects factor showed no main effect of group [$F(1,25) = 1.124$, $p = .30$, $\eta_p^2 = .04$], nor an interaction between group and word type [$F(3,75) = 2.369$, $p = .10$, $\eta_p^2 = .09$], but a significant main effect of word type [$F(3,75) = 37.438$, $p < .0001$, $\eta_p^2 = .60$]. Bonferroni corrected paired samples *t*-tests, collapsed across groups, showed longer RTs in the cohort condition than in the match condition [$t(27) = 10.33$, $p < .001$, Cohen's $d = 1.95$], whereas the rhyme and unrelated conditions were not significantly different from match [rhyme: $t(27) = 1.181$, $p = .99$, Cohen's $d = .22$; unrelated: $t(27) = -0.181$, $p = .99$, Cohen's $d = .03$]. This likely reflects the greater amount of time required to resolve cohort mismatches, which shared word-initial overlap with expected words, whereas rhyme and unrelated mismatches were more phonologically dissimilar from expected words.

A similar pattern was seen for accuracy, marked by a marginal effect of group [$F(1,26) = 3.448$, $p = .08$, $\eta_p^2 = .12$] due to lower accuracy in the SLI group, but no group × word type interaction [$F(3,75) = 1.902$, $p = .15$, $\eta_p^2 = .07$]. There was a main effect of word type [$F(3,75) = 9.027$, $p < .0001$, $\eta_p^2 = .27$], with Bonferroni corrected paired samples *t*-tests collapsed across groups showing lower accuracy on the cohort condition compared to match [$t(27) = -3.31$, $p = .02$, Cohen's $d = .63$], whereas the rhyme and unrelated conditions did not differ from match [rhyme: $t(27) = 1.90$, $p = .40$, Cohen's $d = .36$; unrelated: $t(27) = 0.692$, $p = .99$, Cohen's $d = .13$]. This again is likely the consequence of the word-initial overlap with expected words in the cohort condition rendering subjects more prone to responding 'yes' than they were for the other two mismatch conditions.

3.2. ERP results

3.2.1. Early auditory processing

We first examined the prediction that children with SLI should show differences in auditory sensory ERP components compared to TD children. To do this, we examined the N100 response as an index of early auditory cortical processing. An initial inspection of the N100 data (Fig. 1) suggested a difference in the relative latency of this component across groups, which makes it difficult to directly compare amplitudes across groups at any given time window.[3] For this reason our analysis focused instead on comparing the latency of this component across groups.

Results from repeated measures ANOVAs comparing 50% fractional area latency between groups (Table 3) revealed a significant region × group interaction for medial electrodes [$F(2,52) = 3.305$, $p = .05$, $\eta_p^2 = .11$]. Analysis of simple effects showed that the typically developing group had an earlier fifty percent fractional area latency than the SLI group in both frontal (F3 and F4) and central (C3 and C4) sites [frontal: $F(1,26) = 6.730$, $p = .02$, $\eta_p^2 = .21$; central: $F(1,26) = 4.939$, $p = .04$, $\eta_p^2 = .16$]. In addition, there was a main effect of group in lateral sites [$F(1,26) = 4.523$, $p = .04$, $\eta_p^2 = .15$], with the typically developing group again showing an earlier fifty percent fractional area latency than the SLI group.

3.2.2. Phonological and lexical processing

PMN. Condition-wise waveforms for each group are shown in Figs. 2 and 3, while difference waves compared between groups for each of the respective mismatch conditions are presented in Figs. 4–6. For the PMN component (Table 4), there was no interaction between group and any other factor, nor was there a main effect of group in any column, suggesting that the PMN response was comparable between the two groups of children. To characterize the nature of this PMN response, we noted that there was a main effect of word type in midline and lateral columns [midline: $F(2,52) = 7.911$, $p = .001$, $\eta_p^2 = .23$; lateral column: $F(2,52) = 3.539$, $p = .04$, $\eta_p^2 = .12$], as well as a three-way interaction between hemisphere, region, and word type in the medial column [$F(4,104) = 3.788$, $p = .02$, $\eta_p^2 = .13$]. To investigate the nature of the three-way interaction in the medial column, we did separate two-way repeated measures ANOVAs in the left and right hemispheres. In the right hemisphere, there was a main effect of word type [$F(2,54) = 7.687$, $p = .001$, $\eta_p^2 = .22$], while in the left hemisphere, there was a significant interaction between region and word type [$F(4,108) = 3.099$, $p = .04$, $\eta_p^2 = .10$], with step-down ANOVAs showing that there was a main effect of word type at F3 [$F(2,54) = 3.661$, $p = .04$, $\eta_p^2 = .12$], C3 [$F(2,54) = 6.710$, $p = .003$, $\eta_p^2 = .20$], and P3 [$F(2,54) = 10.566$, $p = .001$, $\eta_p^2 = .28$]. Bonferroni corrected paired samples *t*-tests showed a smaller amplitude PMN in the cohort versus rhyme conditions [midline: $t(27) = 2.70$, $p = .04$, Cohen's

[3] Analysis of mean amplitude for the N100 window showed that in all columns, there was not a main effect of group, nor was there a significant interaction between group and any within-subjects factor.

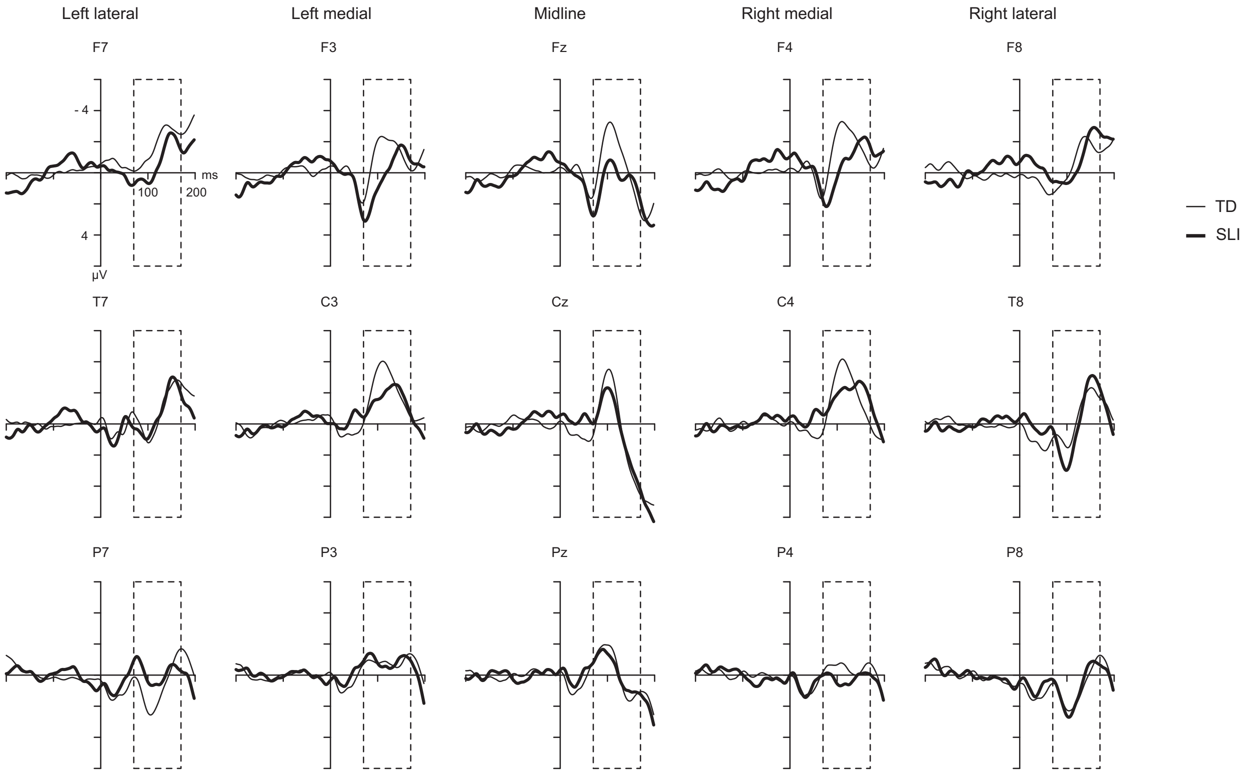

Fig. 1. Grand average waveforms for the match condition in each group, showing the portion of the waveform from −200 to 200 ms. The box delineates the window used to analyze the 50% fractional area latency of the N100 (80–180 ms). Especially in fronto-central electrodes, the 50% fractional area latency was later in the SLI group than it was in the TD group.

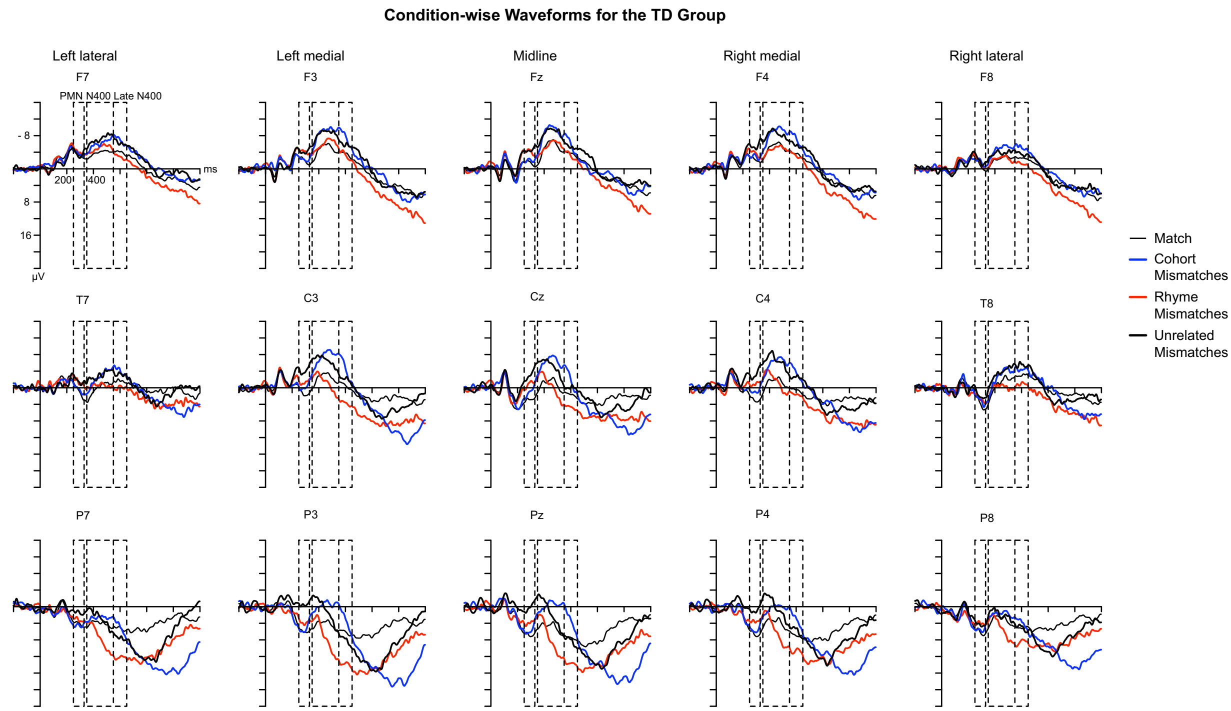

Fig. 2. Condition-wise waveforms for the TD group for the match condition and the three mismatch conditions. The boxes delineate the PMN (250–330 ms), N400 (350–550 ms), and late N400 windows (550–650 ms) used in subsequent statistical analysis.

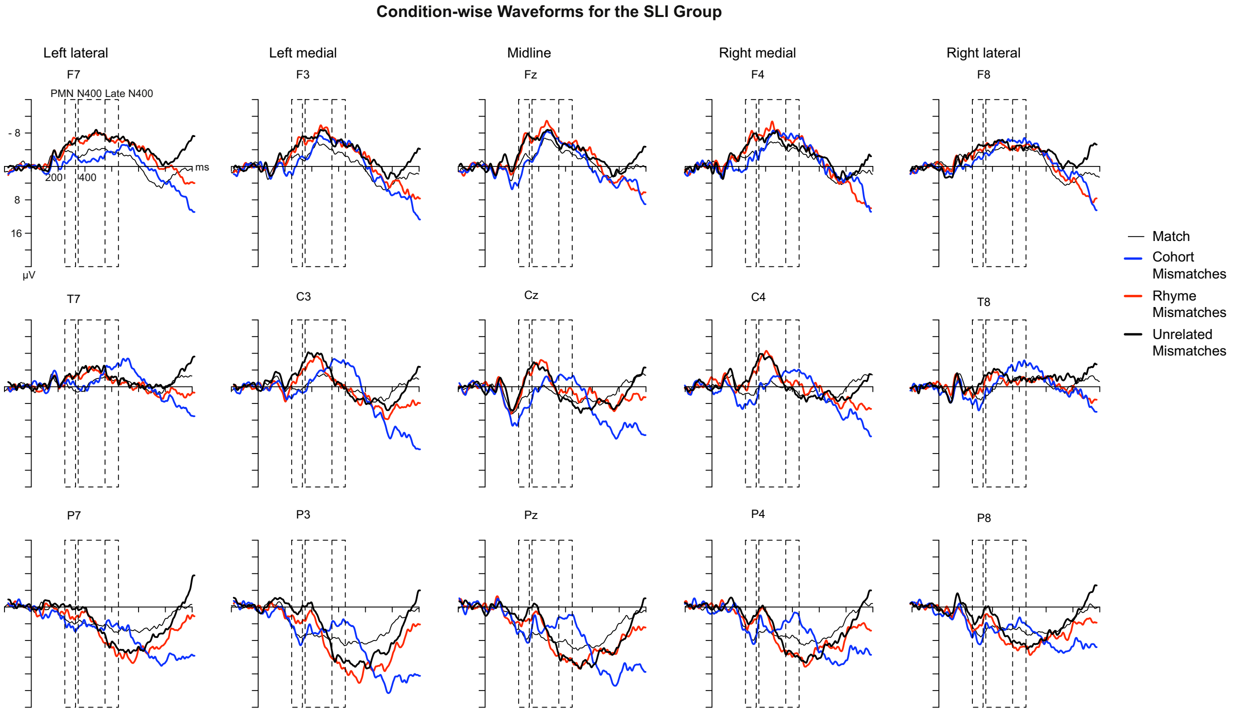

Fig. 3. Condition-wise waveforms for the SLI group for the match condition and the three mismatch conditions. The boxes delineate the PMN (250–330 ms), N400 (350–550 ms), and late N400 windows (550–650 ms) used in subsequent statistical analysis.

d = .51; right medial column: $t(27)$ = 2.63, p = .04, Cohen's d = .50], as well as in the cohort versus unrelated conditions [midline: $t(27)$ = 4.25, p = .001, Cohen's d = .80; right medial column: $t(27)$ = 3.92, p = .002, Cohen's d = .74; F3: $t(27)$ = 2.70, p = .04, Cohen's d = .51; C3: $t(27)$ = 4.41, p = .001, Cohen's d = .83; P3: $t(27)$ = 5.15, p = .001, Cohen's d = .97; lateral column: $t(27)$ = 3.05, p = .02, Cohen's d = .58].

N400. There was a significant interaction between word type and group in the midline and medial columns for the N400 component [midline: $F(2,52)$ = 3.861, p = .03, $\eta_p^2 = .13$; medial column: $F(2,52)$ = 4.053, p = .02, $\eta_p^2 = .14$]. Analysis of simple effects showed that in the rhyme condition, the children with SLI had a more negative N400 amplitude within this window compared to typically developing children [midline: $F(1,26)$ = 4.612, p = .04, $\eta_p^2 = .15$; medial column: $F(1,26)$ = 4.286, p = .05, $\eta_p^2 = .14$], which is clearly apparent in Fig. 5. Note that we also observed significant word type × region interactions in the midline column [$F(4,104)$ = 4.015, p = .02, $\eta_p^2 = .13$], and a significant three-way interaction of word type, region, and hemisphere in the medial and lateral columns [medial column: $F(4,104)$ = 2.785, p = .05, $\eta_p^2 = .10$; lateral column:

Table 3
Summary of ANOVAs for fifty-percent fractional area latency of the N100, with one between-subjects factor of group (2), and either one within-subjects factor of anterior–posterior region (3) for the midline column, or two within-subjects factors of hemisphere (2) and anterior–posterior region (3) for medial and lateral columns.

Effect	df	Midline	Medial	Lateral
Group F p/η_p^2	1,26	1.248 .27/.05	3.851 .06/.13	4.523 .04/.15
Region	2,52	.209 .78/.01	.387 .68/.02	2.159 .14/.08
Region × Group	2,52	.988 .37/.04	3.305 .05/.11	.387 .64/.02
Hemisphere	1,26	–	.080 .78/.003	.061 .81/.002
Hemisphere × Group	1,26	–	3.225 .08/.11	.030 .86/.001
Hemisphere × Region	2,52	–	.576 .55/.02	1.171 .32/.04
Hemi × Region × Group	2,52	–	2.488 .10/.09	.172 .83/.01

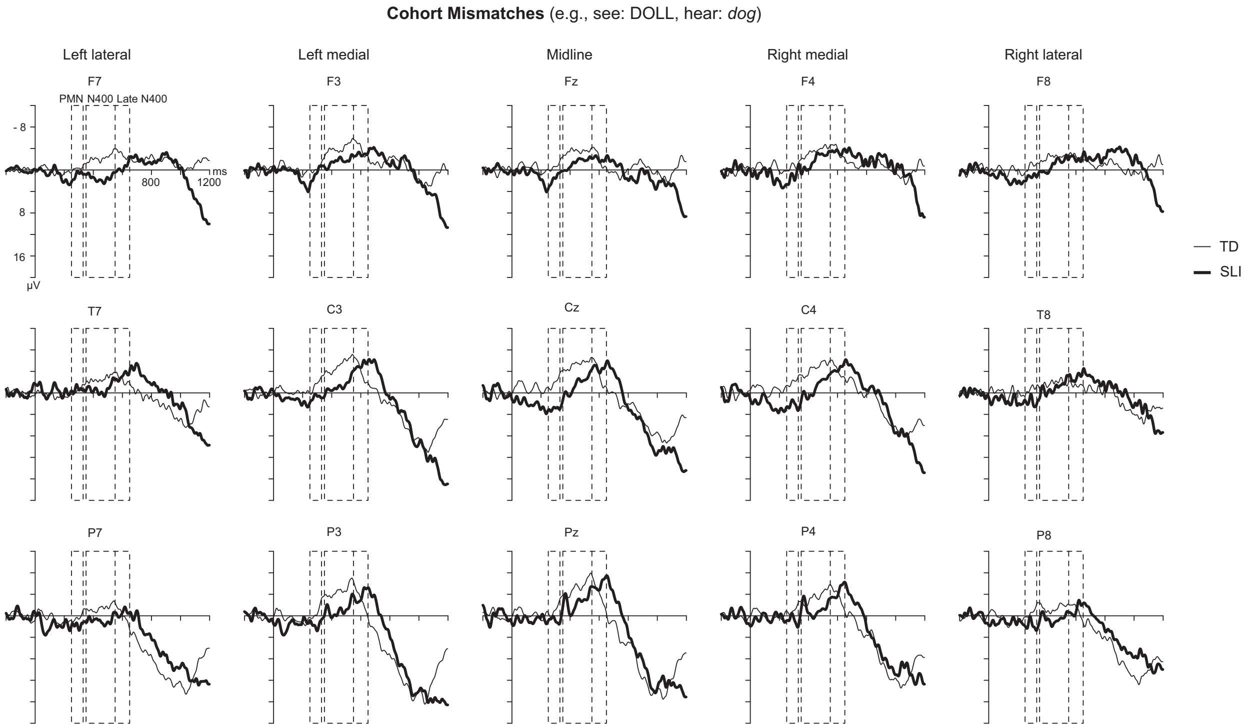

Fig. 4. Difference waveforms for the cohort condition in each group, which were generated by subtracting the respective match condition in each group from the raw waveforms for the cohort mismatch condition. The boxes delineate the PMN (250–330 ms), N400 (350–550 ms), and late N400 windows (550–650 ms).

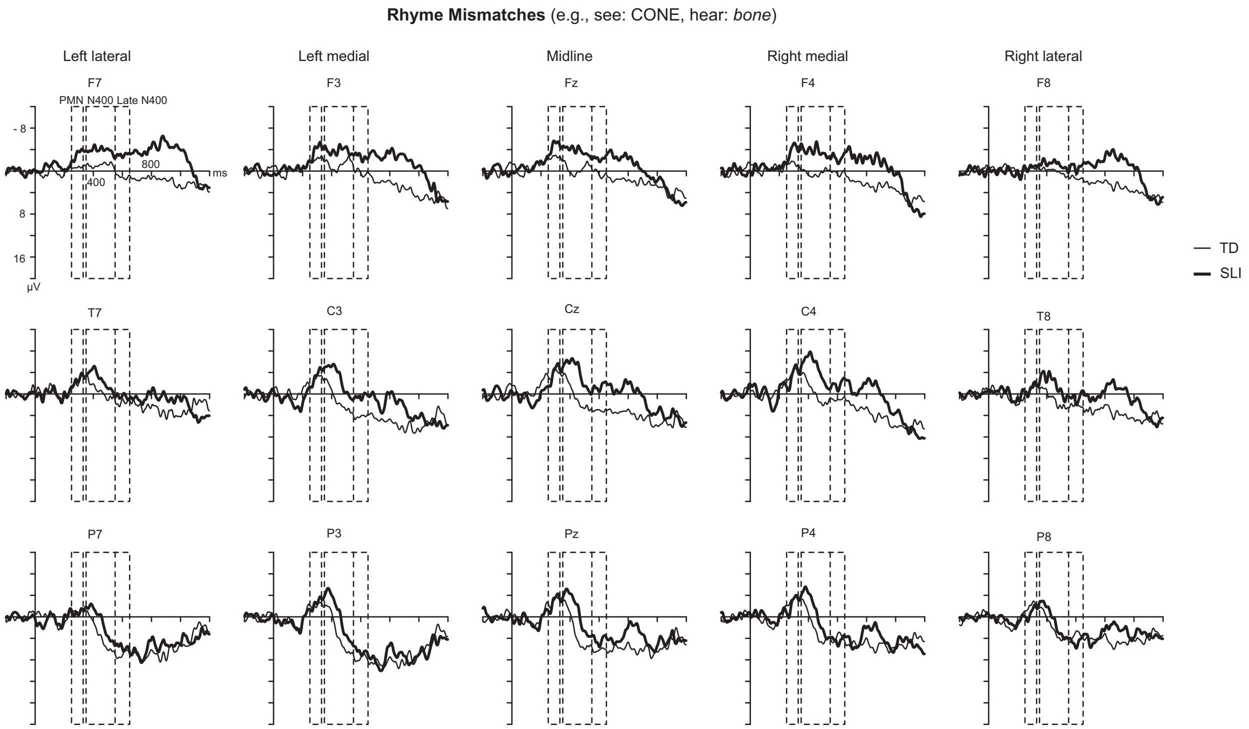

Fig. 5. Difference waveforms for the rhyme condition in each group, which were generated by subtracting the respective match conditions in each group from the raw waveforms for the rhyme mismatch condition. The boxes delineate the PMN (250–330 ms), N400 (350–550 ms), and late N400 windows (550–650 ms). Differences between groups can be observed in the N400 window, in which the N400 amplitude is larger in the children with SLI compared to the TD children especially in midline and medial columns.

Table 4

Summary of ANOVAs for mean amplitude of the PMN, N400, and late N400 with one between-subjects factor of group (2), and either one within-subjects factor of anterior–posterior region (3) for the midline column, or two within-subjects factors of hemisphere (2) and anterior–posterior region (3) for medial and lateral columns.

Effect	df	PMN			N400			Late N400		
		Midline	Medial	Lateral	Midline	Medial	Lateral	Midline	Medial	Lateral
Group *F* p/η_p^2	1,26	.715 .41/.03	.415 .53/.02	.022 .88/.001	.001 .98/.001	.001 .99/.001	.003 .96/.001	.207 .65/.01	.002 .96/.001	.005 .94/.001
Word type	2,52	7.911 .001/.23	8.339 .001/.24	3.539 .04/.12	2.224 .12/08	2.824 .07/.10	1.751 .19/.06	7.876 .01/.23	9.307 .001/.26	4.715 .01/.15
Region	2,52	.488 .62/.02	1.637 .21/.06	.571 .53/.02	1.303 .28/.05	4.590 .02/.15	9.487 .001/.27	6.178 .01/.19	27.673 .001/.52	27.862 .001/.52
Hemisphere	1,26	–	.025 .88/.001	1.013 .32/.04	–	.028 .87/.001	.649 .43/.02	–	4.686 .04/.15	.094 .76/.01
Word type × Group	2,52	.909 .41/.03	.738 .48/.02	.778 .46/.03	3.861 .03/.13	4.053 .02/.14	1.920 .16/.07	1.564 .22/.06	1.483 .24/.05	.758 .47/.03
Region × Group	2,52	2.789 .07/.10	2.506 .10/.09	.528 .55/.02	.009 .98/.001	.170 .78/.01	.301 .67/.01	.228 .73/.01	1.458 .24/.05	1.005 .35/.04
Hemisphere × Group	1,26	–	1.198 .28/.04	1.558 .22/.06	–	.070 .79/.003	.111 .74/.004	–	1.049 .32/.04	.355 .56/.01
Region × Word type	4,104	1.259 .30/.05	1.391 .26/.05	1.158 .33/.04	4.015 .02/.13	2.830 .05/.10	1.959 .14/.07	17.016 .001/.40	9.932 .001/.28	5.868 .01/.18
Region × Word type × Group	4,104	1.132 .34/.04	.408 .71/.02	.533 .63/.02	.391 .73/.02	.463 .68/.02	.257 .81/.01	1.741 .18/.06	1.587 .21/.06	2.767 .06/.10
Hemisphere × Word type	2,52	–	.209 .79/.01	.298 .72/.01	–	.962 .37/.04	1.177 .311/.04	–	2.698 .08/.09	.107 .89/.01
Hemisphere × Word type × Group	2,52	–	.086 .90/.003	.237 .76/.01	–	.558 .54/.02	.676 .49/.03	–	.626 .53/.02	1.127 .33/.04
Hemisphere × Region	2,52	–	.084 .88/.003	2.354 .11/.08	–	3.233 .06/.11	4.614 .02/.15	–	6.003 .01/.19	6.872 .01/.21
Hemisphere × Region × Group	2,52	–	.634 .50/.02	.689 .49/.03	–	.271 .74/.01	.131 .86/.01	–	.319 .71/.01	.450 .60/.02
Hemisphere × Region × Word type	4,104	–	3.788 .02/.13	1.508 .22/.06	–	2.785 .05/.10	5.797 .001/.18	–	3.911 .02/.13	4.464 .01/.15
Hemi × Region × Type × Group	4,104	–	1.141 .34/.04	1.357 .26/.05	–	.738 .53/.03	1.765 .16/.06	–	.512 .63/.02	1.084 .36/.04

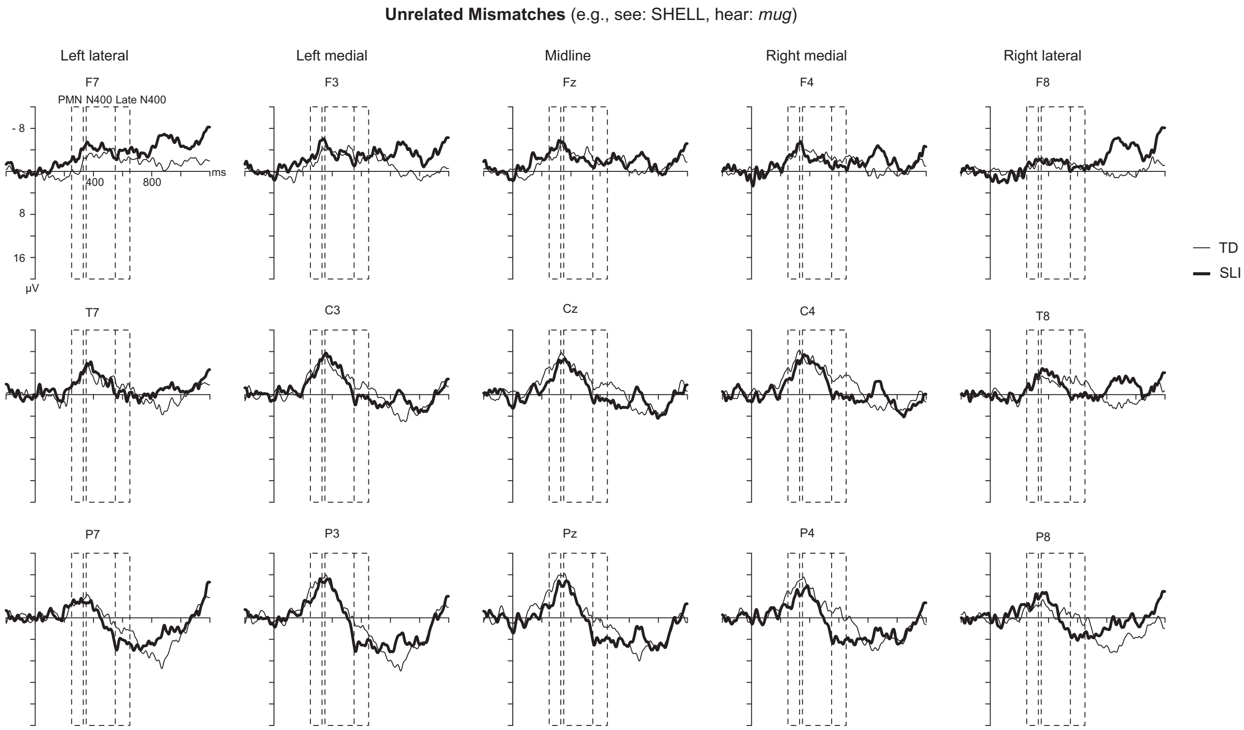

Fig. 6. Difference waveforms for the unrelated condition in each group, which were generated by subtracting the respective match conditions in each group from the raw waveforms for the unrelated mismatch condition. The boxes delineate the PMN (250–330 ms), N400 (350–550 ms), and late N400 windows (550–650 ms).

Table 5
Correlations between ERP measures and non-verbal IQ/SES.

ERP measure	Correlation with non-verbal IQ		Correlation with SES	
	r	p	r	p
N100				
Mean fifty percent fractional area latency across F3 and F4	−.16	.56	.21	.27
Mean fifty percent fractional area latency across C3 and C4	−.002	.99	−.09	.64
Mean fifty percent fractional area latency across the lateral columns	−.07	.73	−.12	.54
N400				
Mean amplitude for rhyme mismatches minus match across the midline column	.30	.12	−.14	.47
Mean amplitude for rhyme mismatches minus match across the medial columns	.25	.20	−.15	.45

$F(4,104) = 5.797$, $p = .001$, $\eta_p^2 = .18$], suggesting that the different word type conditions differed from one another in distribution of the N400 component; importantly though, this pattern did not differ between groups.

Late N400. The only significant interaction involving group was a marginal three-way interaction between region, word type, and group in the lateral column [$F(4,104) = 2.767$, $p = .06$, $\eta_p^2 = .10$]. To investigate the nature of this interaction, we collapsed across hemispheres and performed separate step down repeated-measures ANOVAs for each region. This analysis did not reveal a significant interaction between word type and group in any region.

3.2.3. *Correlations with non-verbal IQ and SES*

To ensure that the reported effects were not the result of differences in non-verbal IQ or SES, we correlated each of these variables with the ERP measures that showed significant groupwise differences; namely, for the N100, the mean fifty percent fractional area latency across F3 and F4, across C3 and C4, and across the lateral columns; for the N400, the mean amplitude for rhyme mismatches minus match for the midline and medial columns. None of these ERP measures were significantly correlated with either non-verbal IQ or SES, as detailed in Table 5.

4. Discussion

The aim of the present study was to compare the time course of auditory word recognition in children with specific language impairment (SLI) and children of the same age with typical language development. We employed a picture–word matching task in which we measured ERP responses to expected versus unexpected auditory words.

Our rationale for using this type of task is that viewing a picture cues the phonological representation of the pictured word, such that a subsequent mismatching auditory cue will modulate ERP components related to spoken word recognition. Specifically, when presented with a spoken word, a listener maps incoming auditory information onto an activated phonological form. Ensuing ERP components time-locked to the presentation of the auditory word are predicted to be modulated based on the extent to which the listener detects that this word does not match a previously activated phonological template. This process depends critically on the ability to discriminate subtle acoustic cues for different phonemes, the strength of the currently activated representation cued by the picture stimulus, and the ability to suppress lexical alternatives. We have previously found this task to be sensitive to phonological similarity in both adults and children, yielding temporally differentiable effects that allow us to decompose the time course of speech processing and spoken word recognition (Desroches et al., 2009; Archibald and Joanisse, 2011, 2012; Malins and Joanisse, 2012; Desroches et al., 2013). In this study we expected that examining the interference effects of different types of phonological mismatches (i.e., cohorts and rhymes) on ERP components associated with phonological and lexical processing would provide a closer specification of speech perception in children with SLI.

Turning first to early auditory processing, we observed that the 50% fractional area latency of the N100 was earlier in typically developing (TD) children than it was in children with SLI, especially at fronto-central electrodes. This is in line with what has been reported in prior studies finding that when presented with sequences of tones, children with SLI showed key age-related differences in the nature of N100 components, with respect to latency, magnitude and scalp distribution (Tonnquist-Uhlén et al., 1996; McArthur and Bishop, 2004). These results were thought to be the result of a maturational delay of auditory cortex in children with SLI. Our data fit with this view, as it has been observed that during development, typically developing children aged 5–6 show a broad positivity between 80 and 180 ms, while older children aged 8–11 show a bifurcation in this window as the N100 component emerges (Ponton et al., 2000; Sussman et al., 2008). Furthermore, as children approach adolescence, this N100 component becomes progressively more prominent. Following this logic, if the typically developing children had more mature auditory cortices, they would be expected to display a prominent N100 peak early within the window from 80 to 180 ms, explaining why the fifty-percent fractional area latency was attained relatively early in these children. In contrast, if the children with SLI had more immature auditory cortices, we would expect that they would display N100s smaller in amplitude, and the 80–180 ms window would hence be dominated mostly by the later P200. This explains why they reached the fifty-percent fractional area latency at a later point in the window. Interestingly, this view of maturational differences is also supported by recent work by Choudhury and Benasich (2011), who found that infants and young children with a family history of language impairment showed differences in the maturation of auditory ERPs compared to children without a family history of language impairment. In the context of these findings, it could be the case that the children in the present study have experienced fundamental differences in cortical processing of basic auditory information during speech perception for many years. This could then account for why they showed impairments further downstream in phonological–lexical processing at the time of testing.

The contribution of the present study is the ability to also observe how these apparent differences in N100 ERPs influence subsequent auditory word recognition processes. Prior studies to this effect have tended to focus either specifically on nonspeech auditory sounds such as tones (Tonnquist-Uhlén et al., 1996; McArthur and Bishop, 2004) or in some cases nonsense syllables (Breier et al., 2003). The design of the present study allows us to examine how N100 differences relate to ERP indices of later-going speech perception mechanisms. Indeed, our data suggest that differences in the N100 response in SLI do not yield a general slowing or reduction in later-going speech-related ERP components; rather we found that language impaired children had difficulties only in resolving specific types of phonological mismatches. The mismatch conditions in our study were designed to elicit different patterns of PMN and N400 responses, and therefore can allow us to tease apart subtle differences in the mechanisms indexed by them. In typical adult listeners, PMN responses for word initial mismatches (e.g., rhyme and unrelated conditions) are known to elicit different modulations compared to cohort mismatches that overlap in initial consonants with target words (e.g., see: DOLL, hear: *dog*; Connolly and Phillips, 1994). We thus reasoned that group differences in the PMN would reveal difficulties in recognizing word overlap at the phoneme level in SLI. Interestingly, analyses revealed that the PMN was similarly modulated in both groups of children, in that there was a significant modulation of the PMN in the rhyme and unrelated conditions compared to the cohort condition, as rhyme and unrelated mismatches differed from expectations in word-initial phonemes while cohort mismatches did not. However, there was no interaction between group and any other factor, nor a main effect of group. This finding suggests that, like typically developing controls, children with SLI can generate phonological expectations and readily detect violations of these expectations in an online fashion.

Effects observed for the N400 component, however, suggest differences in lexical processing between the two groups. The rationale for this is that while the PMN is thought to reflect phonemic processing, the N400 is instead thought to index processing of the higher-level structure of words; for example, recognizing rhyme overlap between words (Dumay et al., 2001; Radeau et al., 1998). An N400 effect for a mismatch trial suggests that a listener has detected that a word form does not match expectations, and the size of this effect is thought to reflect the amount of indecision and/or interference a listener experiences during this process (Desroches et al., 2009). With this in mind, the N400 component showed clear group differences for the rhyme condition (see: CONE, hear: *bone*). As the difference waves in Fig. 5 illustrate, typically developing children show a *positivity* compared to match in midline and medial electrodes, similar to what has been reported by Desroches et al. (2009), and suggesting that the TD children in the present study also demonstrated a similar rhyme competitor effect. One way of accounting for this effect is via continuous mapping models such as TRACE (McClelland and Elman, 1986): the picture stimulus activates the phonological form of its corresponding word, which then spreads activation to its constituent phonemes via top-down lexical → phoneme level connections. These in turn can activate rhyming word forms that share constituent phonemes via bottom-up phoneme → lexical connections. At the lexical level, connections between words are mutually inhibitory, and so rhyming words are suppressed at the lexical level as disconfirming auditory information arrives. However, the phonemes that comprise the rime will remain partially active, and so as the word unfolds, rhyme mismatches are more easily recognized than unrelated words, for which these prior activations have to be overcome. The result is facilitation within the N400 window for rhyming words versus non-rhyming forms, a finding that has been observed in both the auditory (Praamstra et al., 1994; Radeau et al., 1998; Coch et al., 2002) and visual modalities (Rugg, 1984; Grossi et al., 2001).

Notably, children in the SLI group did not show this same effect. As can be seen in Figs. 2 and 3, rhyming words were treated more similarly to the phonologically unrelated words in the SLI group than they were in the TD group. This could be for several reasons. First, it could be the case that rhyming words do not receive the same level of prior activation in children with SLI because these children are not as sensitive to rhyme similarity as their typically developing peers. This lack of sensitivity to rhymes is somewhat similar to that observed in a much younger group of children with SLI (Gray et al., 2012); however, it is different from the results of Seiger-Gardner and Brooks (2008), who did not find any differences in rhyme sensitivity between typically developing school-aged children and age-matched children with SLI, and instead found differences between groups in onset-related inhibition of words. We think this difference has to do with the task used to assess rhyme sensitivity: in the cross-modal picture–word interference paradigm used by Seiger-Gardner and Brooks (2008), children are asked to name pictures aloud, and auditory distractors are presented either before, during, or after viewing the picture, leading to inhibitory versus facilitative effects (e.g., Brooks and MacWhinney, 2000). In the current picture–word matching task, pictures were always presented before auditory words, and preceded auditory words by a much longer period of time, thus setting up very strong expectations of auditory input. In addition, children were not required to produce words. Hence what we are tapping into are the processes that underlie detecting whether a spoken word mismatches expectations, rather than what is required to program a motor response. It should be noted that even within the current study, this mismatch between behavioral and ERP results is apparent: there was no main effect of group on reaction time for the matching judgment, and at best a marginal effect on accuracy, yet there was a difference between the groups in terms of ERP responses. This pattern of findings is not unusual in the ERP literature (e.g., Brown and Hagoort, 1993), including past studies on SLI (e.g., Shafer et al., 2005), and highlights the sensitivity of techniques like ERP to uncover subtle deficits not always apparent in overt behavioral measures.

An alternative explanation for a lack of attenuation of the N400 for rhyming words could be that children with SLI activate rhyming words as readily as their typically developing peers, but do not suppress these alternatives to the same extent at the lexical level once they receive auditory information incompatible with their expectations. As a result, children with SLI might experience a longer duration of lexical competition from rhyming words, which explains why they showed evidence of competition in the N400 window – as indexed by a greater negativity compared to match – while the TD children were instead experiencing facilitation. This explanation fits with a recent study by McMurray et al. (2010), who found that in an eyetracking study using the visual world paradigm, compared to typically developing individuals, adolescents with SLI looked at cohort and rhyme competitors more often as target words unfolded. McMurray et al. (2010) explain this in terms of lexical decay rate: they suggest that lexical items do not remain active for as long in memory in individuals with SLI, and so as a result they fail to inhibit competitor words at the lexical level to the same degree. Consequently, competitor words then become activated to a greater extent based on bottom-up perceptual input. This explanation is compatible with the rhyme effects observed in the current study; however, this theory also predicts differences between groups in the cohort condition, which we failed to observe in all analysis windows. As a result, it seems that perhaps the first explanation better accounts for our present results.

It is also worth considering whether differences between groups in non-verbal IQ and SES might underlie the observed ERP effects. As has been shown in previous studies (Tomblin et al., 1997a,b), socioeconomic status often differs between the families of typically developing children and children with SLI, and SES has been shown to influence certain skills in children with SLI such as knowledge of print (McGinty and Justice, 2009). While SES was found to differ between groups in the current study, it was not correlated with any of the observed ERP effects that showed groupwise differences. This was also the case for non-verbal IQ, which differed between groups but did not explain experimental effects (Finneran et al., 2009). Thus the observed effects are unlikely to be the result of these differences in non-verbal IQ or SES; rather, they are more likely the result of the differences between groups in acoustic and phonological–lexical processing that we have characterized.

4.1. Implications of results

In summary, the children with SLI showed several key differences from TD children in this task: first, a longer latency N100 response early in word recognition, indicating a fundamental difference in how these children process the basic sensory features of speech; and second, a lack of N400 attenuation for rhyming words, indicating a lack of sensitivity to rhymes or an impaired ability to suppress lexical alternatives. Importantly, these deficits occur at the level of acoustic and phonological processing, which is interesting given that SLI is typically described as a deficit in receptive grammar. Indeed a receptive grammar test was used to identify children with SLI in this study, in keeping with standard practices (Tomblin et al., 1996). Thus an important question is whether the speech processing impairment observed here is a viable explanation for these children's receptive grammar deficits.

A potential mechanism for linking speech processing difficulties to grammar deficits is at the level of word learning (Munson et al., 2005). If children with SLI show differences in early auditory processing as well as a lack of sensitivity to phonological relationships such as rhymes, this could make it more difficult to establish highly specified representations for new words. This difficulty is thought to arise in both directions: children with SLI have trouble discriminating subtle distinctions, and so it is harder to establish novel representations for words distinct from words that are phonologically similar to them (Briscoe et al., 2001); second, these children do not use higher-level phonological knowledge as a scaffold in word learning to the same extent as their typically developing peers (Munson et al., 2005). This lack of sensitivity to subtle distinctions between words could be especially problematic for words that signify grammatically important relationships, which can sometimes differ in only one phoneme (e.g., 'cat' versus 'cats', or 'walk' versus 'walked'; see Leonard et al., 2007a,b). In addition, an impairment in using higher-level phonological knowledge would make it difficult to analyze the common features among morphologically related words. For instance learning the progressive *–ing* verb ending requires the learner to analyze the similarity of RUN and RUNNING, and how this relates to the similarity among WALK-WALKING, TALK-TALKING and so on (Joanisse, 2004).

That said, these results must be interpreted with some caution. First, it could also be that phonological, lexical and grammar deficits in SLI are purely epiphenomenal, and reflect a more general deficit (see van der Lely, 2005, for a review of this controversy). The design of the present study cannot adjudicate among these competing causal models, though it does lend some support to the view that in SLI, there is a relationship between low-level auditory difficulties and deficits further downstream in both phonological grammar, or knowledge of the hierarchical organization that governs how phonemes are structured to form words, as well as morphosyntax.

As mentioned above, there has been some work on the development of auditory sensory ERPs such as the N100 in children, and the pattern of deficits observed in SLI resembles what is seen in younger typical language learners (McArthur and Bishop, 2004). That said, much less is known about the development of the later-going language-related ERP components such as the PMN and N400. It remains to be seen whether these differences also represent a delay in the development of these neural processes, or whether they are a true deviation from the expected developmental trajectory. However, we do note that the effects observed for the TD children in our study closely resemble those we have observed for adults (Desroches et al., 2009). Thus, it may be that these later ERP components are established early in life and remain fairly stable across development. If that is the case, deviations from these patterns are not likely to represent a simple maturational delay.

Finally, we note that the general pattern of results reported here is similar to what was observed in a recent study from our laboratory which compared children with dyslexia to same-age controls using the same procedures (Desroches et al., 2013). A key difference is the N100 effect observed in the present study, which was not apparent in children with dyslexia. Notably those children were selected as having a specific reading impairment but normal-range oral language scores. Thus the earlier-going N100 component appears to be specifically related to oral language difficulties and not impaired reading. We have previously proposed that both oral and written language deficits stem from similar problems with processing the phonological forms of words, but that SLI includes additional difficulties with speech perception (Joanisse et al., 2000; Robertson et al., 2009). The finding of early processing differences in SLI further suggests that such difficulties can serve to distinguish between these two types of language disorders. Of course, we must bear in mind that the task used in the current study only taps into one or a few of the constellation of deficits observed in SLI, some of which overlap with those in dyslexia (see Bishop and Snowling, 2004, for a review).

5. Conclusions

The present study sought to characterize deficits in auditory word recognition in children with specific language impairment using ERPs. Results showed that compared to TD children, children with SLI displayed differences in fundamental speech processing as indexed by the N100, which could influence subsequent auditory word recognition processes. In contrast, both groups showed comparable effects of initial-phoneme mismatch as indexed by the PMN, suggesting children with SLI are capable of generating phonological expectations and detecting violations of these expectations in an online fashion similar to that of TD children. Critically though, the two groups did show later-going differences in N400 effects related to lexical competition among rhyming words, suggesting that children with SLI are either not as sensitive to rhyme similarity as their typically developing peers, or do not suppress lexical alternatives to the same extent. This study thus adds to a growing body of work using online processing tasks to better understand the nature of the underlying processing deficits in this pervasive language disorder.

Conflicts of interest

None of the authors declare any conflict of interest in carrying out this study.

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